HIGGS 2024

@ Uppsala, Sweden

November 6, 2024

Status of Triplet Extended Higgs Sector Models in Light of NLO Unitarity and Latest LHC Data

Subrata Samanta

Indian Institute of Technology Kanpur, India

Based on:

D. Chowdhury, P. Mondal, S.S.

arXiv: 2404.18996 [hep-ph]

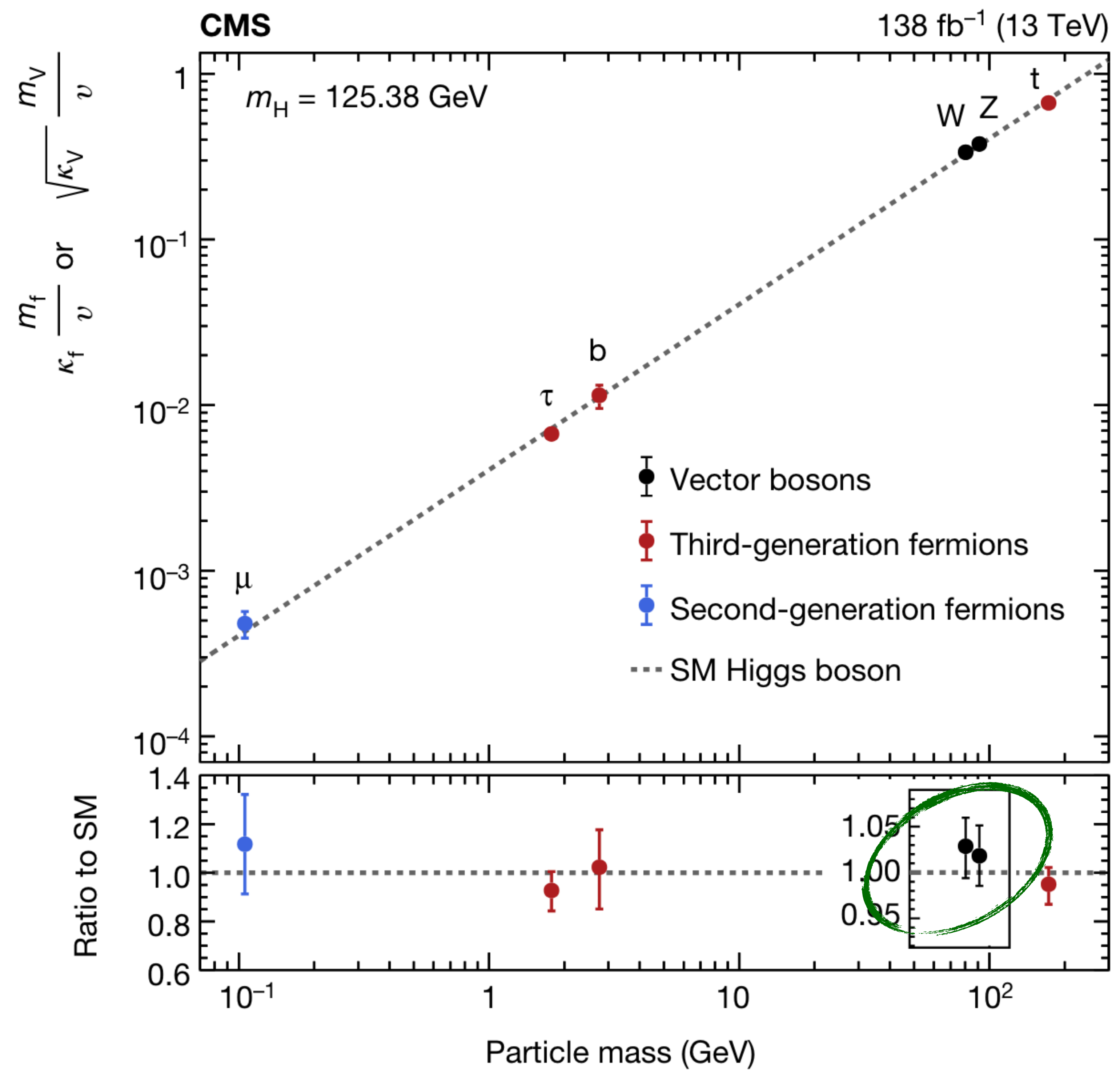
Funded by : IIT Kanpur, Ministry of Education (PMRF), SERB (Govt. of India)

Beyond the Standard Model

- Standard Model (SM) of particle physics is a framework ➡ good agreement with collider data

  Open questions :

  Neutrino masses , Dark Matter ,
  Baryon asymmetry of the Universe (BAU) ,
  Electroweak Phase Transitions (EWPT)



- SM might be a simplified version of a more complicated model

- Do the LHC data preclude the existence of additional multiplets in the scalar sector of the SM ?

Search for BSM @ forefront of particle physics research

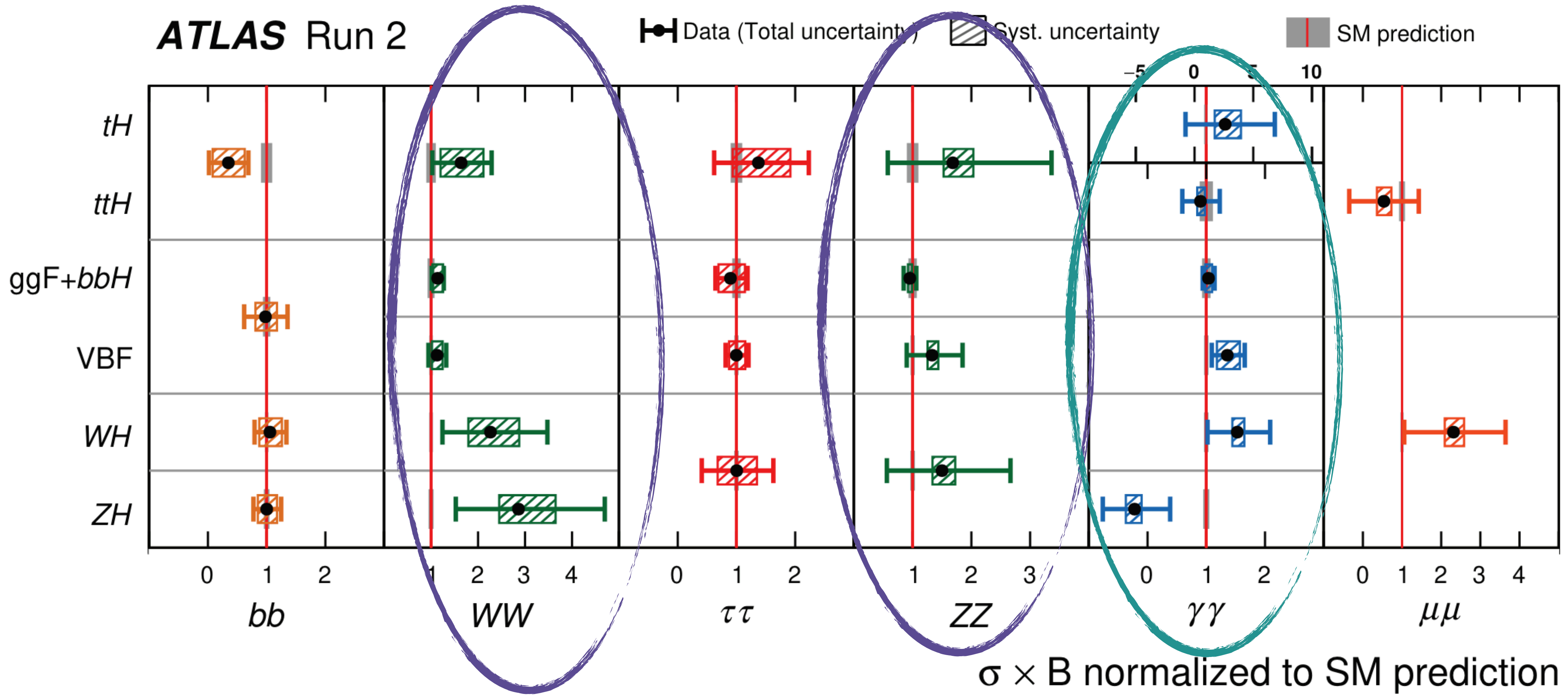
Triplet Extended Higgs Sector

- Both ATLAS and CMS suggest an enhanced rate of WW and ZZ relative to the SM

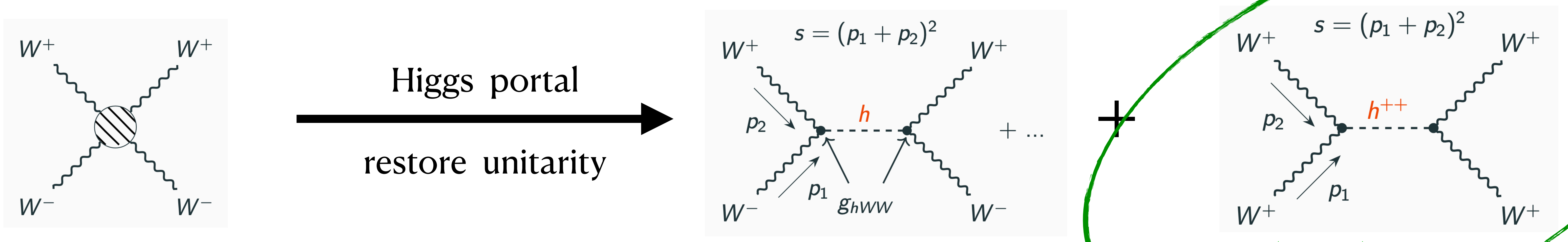
The questions we ask is :

If WW and ZZ rates are enhanced,
how far beyond the SM one must to describe them?

Additional charged Higgs ?



Recap : WW scatterings are weakly interacting or strongly interacting ?



$g_{hWW} > (g_{hWW})_{SM}$

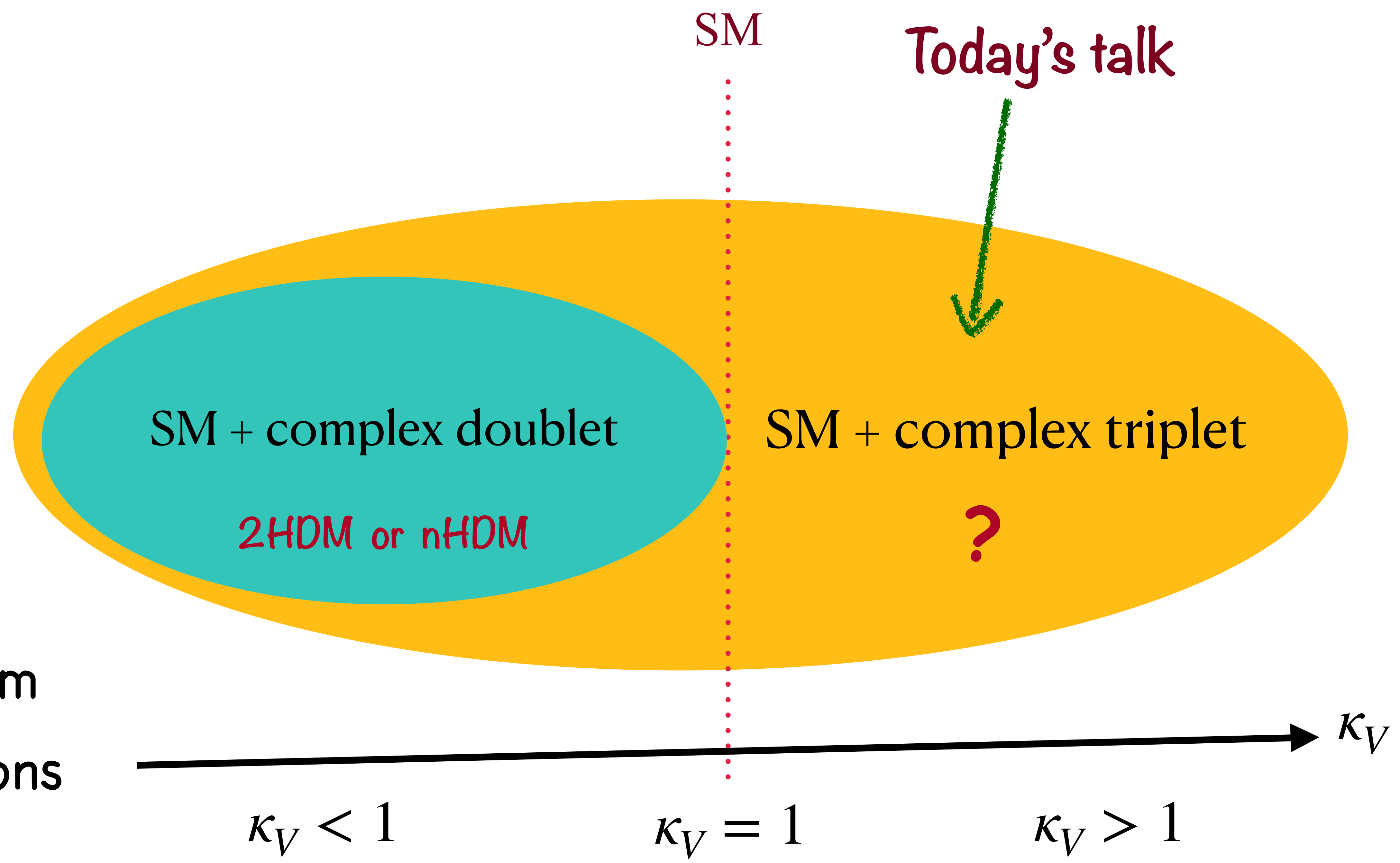
$g_{hWW}^2 - g_{h^{++}WW}^2 = (g_{hWW}^2)_{SM}$

✔ Additional doubly charged Higgs boson plays an important role to restore unitarity at high energies

Triplet Extended Higgs Sector

- Model with triplet extended Higgs sector can explain an enhanced rate of WW and ZZ

  - Doubly charged Higgs boson comes from $SU(2)_L$ triplet through EWSB mechanism



Triplet or higher multiplets leave an imprint on the EWSB mechanism that can be detected via SM-like Higgs couplings to the vector bosons

- ✓ It can also explain neutrino oscillation , EWBG , Dark-Matter puzzle
- ✓ It offers a much richer prospect for collider experiments

Can be probed in particle colliders and in cosmological observatories

Higgs Triplet Models with Custodial Symmetry

- Custodial Symmetry : $M_W^2 = M_Z^2 \cos^2\theta_W$

Rho-parameter, $\rho = \dfrac{M_W^2}{M_Z^2 \cos^2\theta_W}$

At tree-level, $\rho = 1$

- Triplet extended Higgs sector with Custodial Symmetry :

SM doublet $\phi \; (T = 1/2, Y = 1/2)$ + Real triplet $\xi \; (T = 1, Y = 0)$ + Complex triplet $\chi \; (T = 1, Y = 1)$

$\langle\phi\rangle = v_\phi \,, \langle\xi\rangle = v_\xi \,, \langle\chi\rangle = v_\chi$ ⟶ $\rho = 1$ in tree-level if $v_\chi = v_\xi$

* Georgi-Machacek (GM) model :

Equality of triplet VEVs is preserved by the Higgs potential [Georgi, Machacek '85; Chanowitz, Golden '85]

Interactions among the Higgs fields maintained $SU(2)_L \times SU(2)_R$ symmetry

* extended Georgi-Machacek (eGM) model :

Equality of triplet VEVs is obtained by tuning the potential parameters @ tree-level [Kundu, Mondal, Pal '21]

Higgs interactions does not maintained $SU(2)_L \times SU(2)_R$ symmetry

...Similar interactions were considered in 2HDM with softly broken Z_2 symmetry

Extended Georgi-Machacek Model

125 GeV

h H F^0 — CP even

A^0 — CP odd

H^+ F^+ — Singly charged

F^{++} — Doubly charged

- **GM limit :**

h H — m_1

1 constraints

A^0 H^+ — Mass degenerate (m_3)

2 constraints

F^0 F^+ F^{++} — Mass degenerate (m_5)

Consequence of $SU(2)_L \times SU(2)_R$ **symmetry**

GM $\subset$ eGM

Salient features

GM model	**eGM model**
• Scalar multiplets mass degenerate	• Scalar multiplets non mass degenerate ↓ new decay modes open up ↓ search for new physics @ colliders
• Divergent contribution to ρ parameter @ one-loop	• All the counter-terms are present in the Lagrangian
• Only H^+ couples to fermions.	• Both H^+ and F^+ couple to fermions ↓ Much richer flavour physics phenomenology

…slide taken from Poulami Mondal's talk @ Higgs Hunting 2024

Theoretical Constraints

- Positivity of the Higgs potential

$$V^{(4)} = \lambda_\phi(\phi^\dagger\phi)^2 + \lambda_\xi(\xi^\dagger\xi)^2 + \lambda_\chi(\chi^\dagger\chi)^2 + \tilde{\lambda}_\chi\left|\tilde{\chi}^\dagger\chi\right|^2 + \lambda_{\phi\xi}(\phi^\dagger\phi)(\xi^\dagger\xi)$$
$$+\lambda_{\phi\chi}(\phi^\dagger\phi)(\chi^\dagger\chi) + \lambda_{\chi\xi}(\chi^\dagger\chi)(\xi^\dagger\xi) + \kappa_1\left|\xi^\dagger\chi\right|^2 + \kappa_2(\phi^\dagger\tau_a\phi)(\chi^\dagger t_a\chi) + \kappa_3\left[(\phi^T\epsilon\tau_a\phi)(\chi^\dagger t_a\xi) + \text{h.c.}\right] > 0$$

- Yukawa and quartic couplings of the theory need to be in perturbative regime

$y_i < \sqrt{4\pi}$ and $\lambda_i < 4\pi$

- Quartic couplings should satisfy the unitarity conditions @ one-loop

$$\left|a_\ell^{2\to2} - \frac{1}{2}i\right|^2 + \sum_{k>2}\left|a_\ell^{2\to k}\right|^2 = \frac{1}{4}.$$

- NLO corrections to the LO amplitudes should be smaller in magnitude

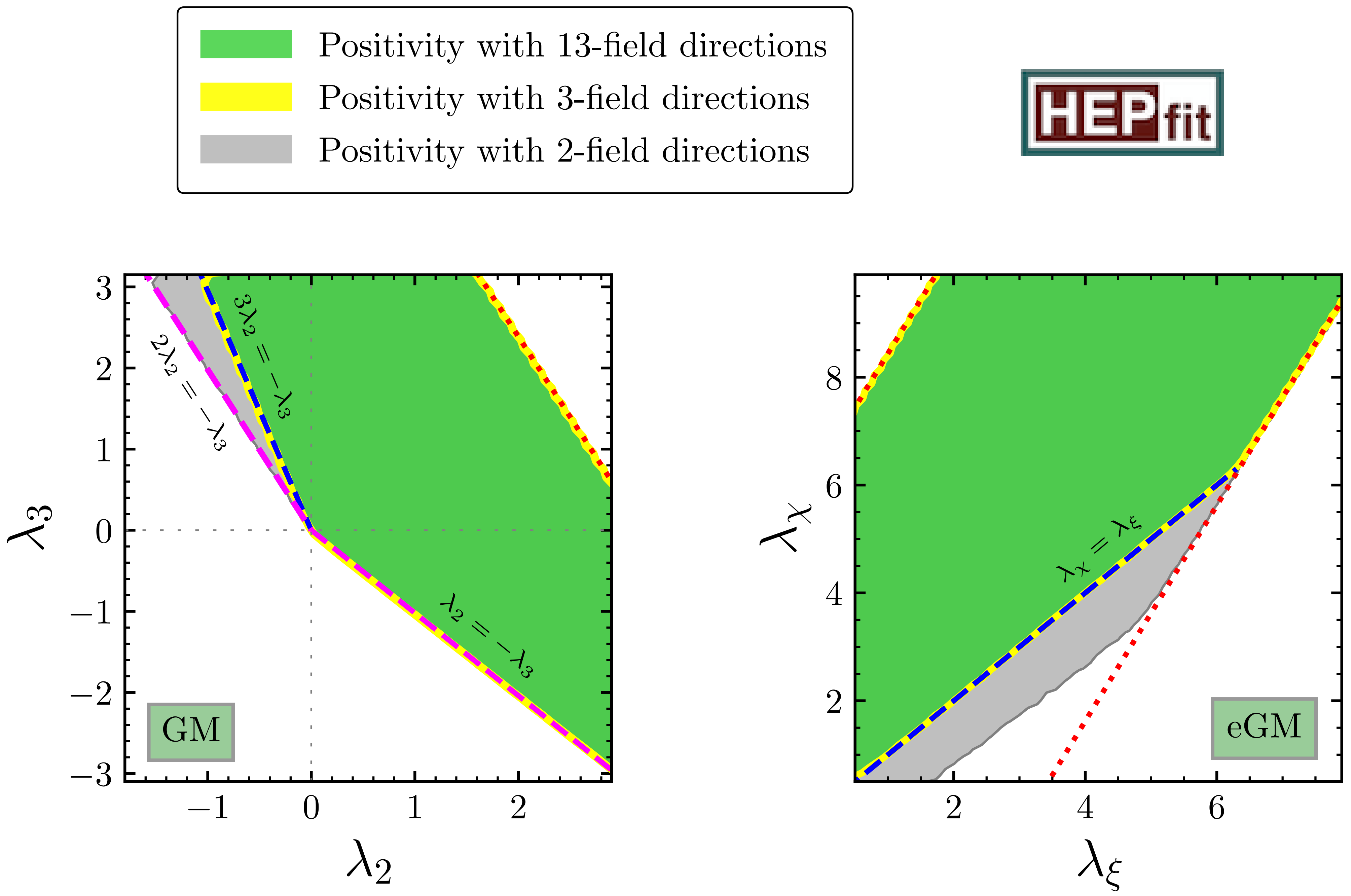
$$|a_\ell^{NLO}| < |a_\ell^{LO}|$$

Positivity of the Higgs Potential

Ensure that boundedness of the potential
in any directions of field space

Numerically, 3-field direction BFB conditions
(neither necessary nor sufficient)
are a very good approximation of
all 13-field direction BFB conditions

[Moultaka, Peyranère '21, D. Chowdhury, P. Mondal, S.S. 2404.18996]



These 3-field direction BFB conditions
are faster numerically

NLO unitarity

For a given $2 \to 2$ process, the unitarity bounds : $|a_\ell - i\frac{1}{2}| \leq \frac{1}{2}$

- LO unitarity : $a_\ell^{LO} \in \mathbb{R}$, $|\mathrm{Re}(a_\ell^{LO})| \leq \frac{1}{2}$
- NLO unitarity : $a_\ell^{NLO} \notin \mathbb{R}$, $|a_\ell^{NLO} - i\frac{1}{2}| \leq \frac{1}{2}$

Weakly interacting theories : $a_\ell^{LO} > a_\ell^{NLO}$ @ 1-loop

These are used to put bound on the potential parameters or exotic Higgs masses in a weakly interacting theory

Prior to the Higgs discovery : LO unitarity : $\lambda \leq \frac{8\pi}{3}$ [Lee, Quigg, Thacker '77]

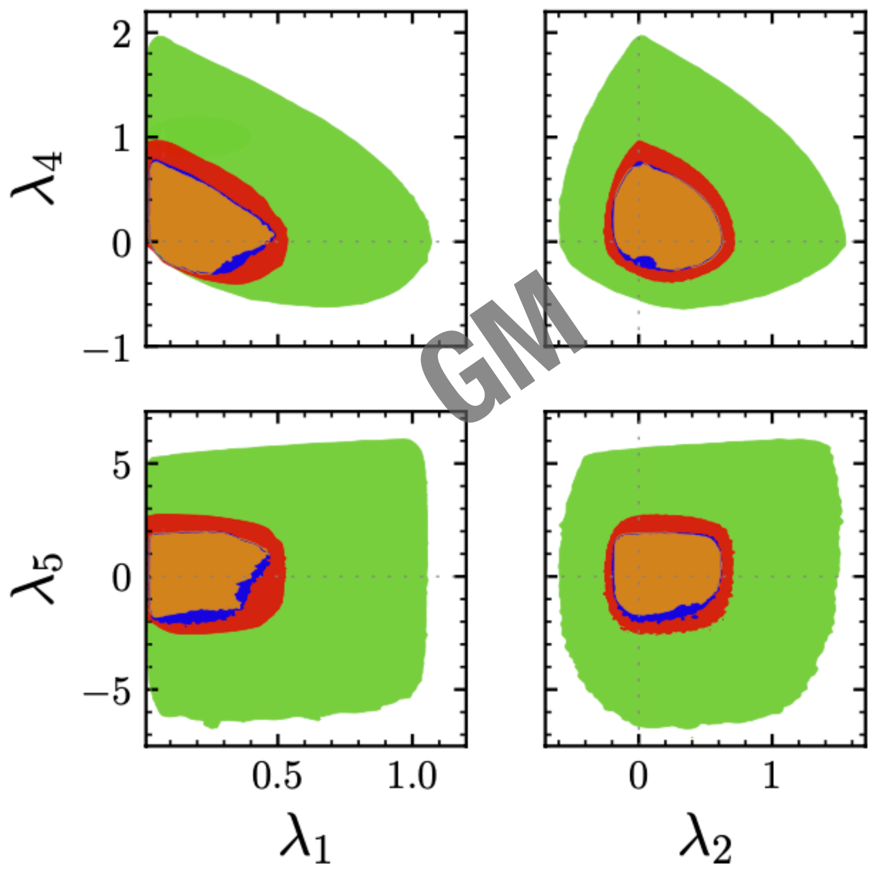
NLO unitarity : $\lambda \leq 2 - 2.5$ [Dawson, Eillenbrock '89; Durand, Johnson, Lopez'92]

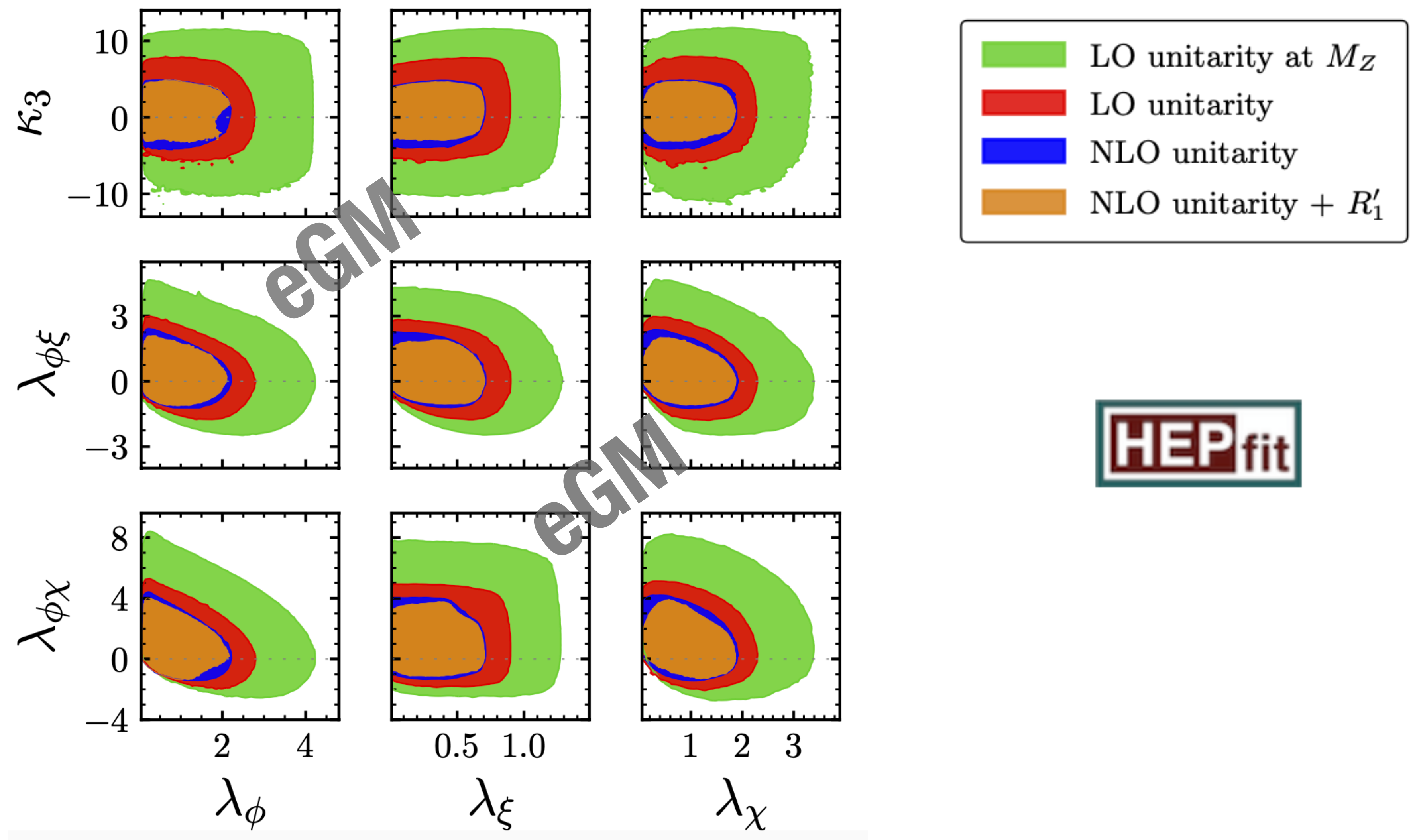
No revised limit @2-loop [Durand, Maher, Riesselmann, 92]

Weakly interacting SM Higgs scenario

- GM and eGM model :

NLO unitarity significantly refine the parameter space





D. Chowdhury, P. Mondal, S.S. 2404.18996

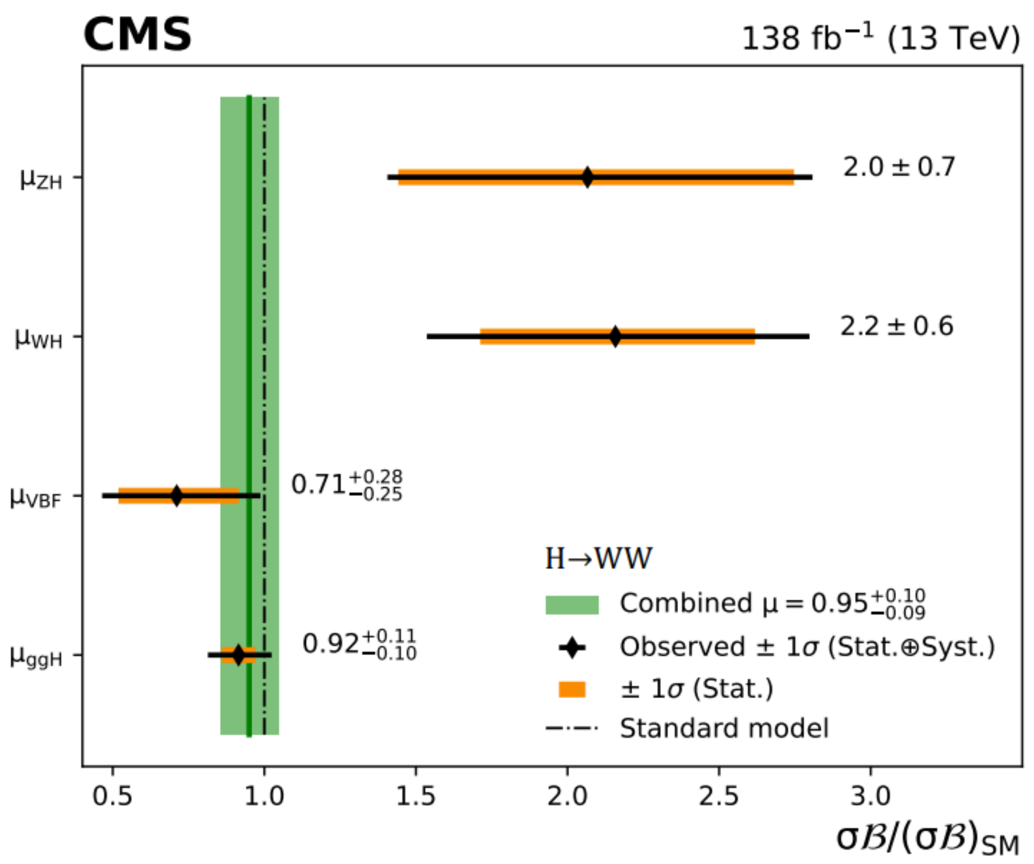
HEPfit

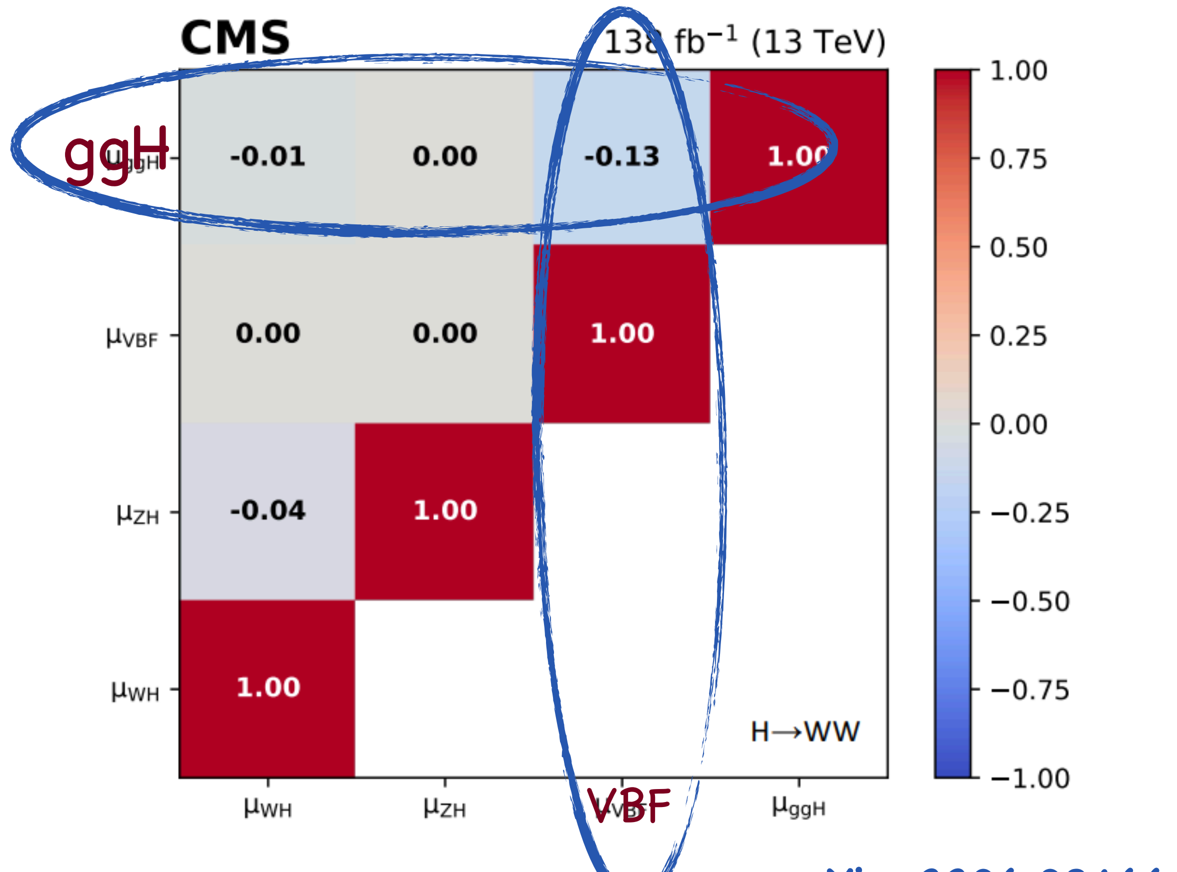
Higgs Signal Strengths

$$\mu_i^f = \frac{\sigma B\,(i \to h \to f)}{\sigma B_{SM}\,(i \to h \to f)}$$

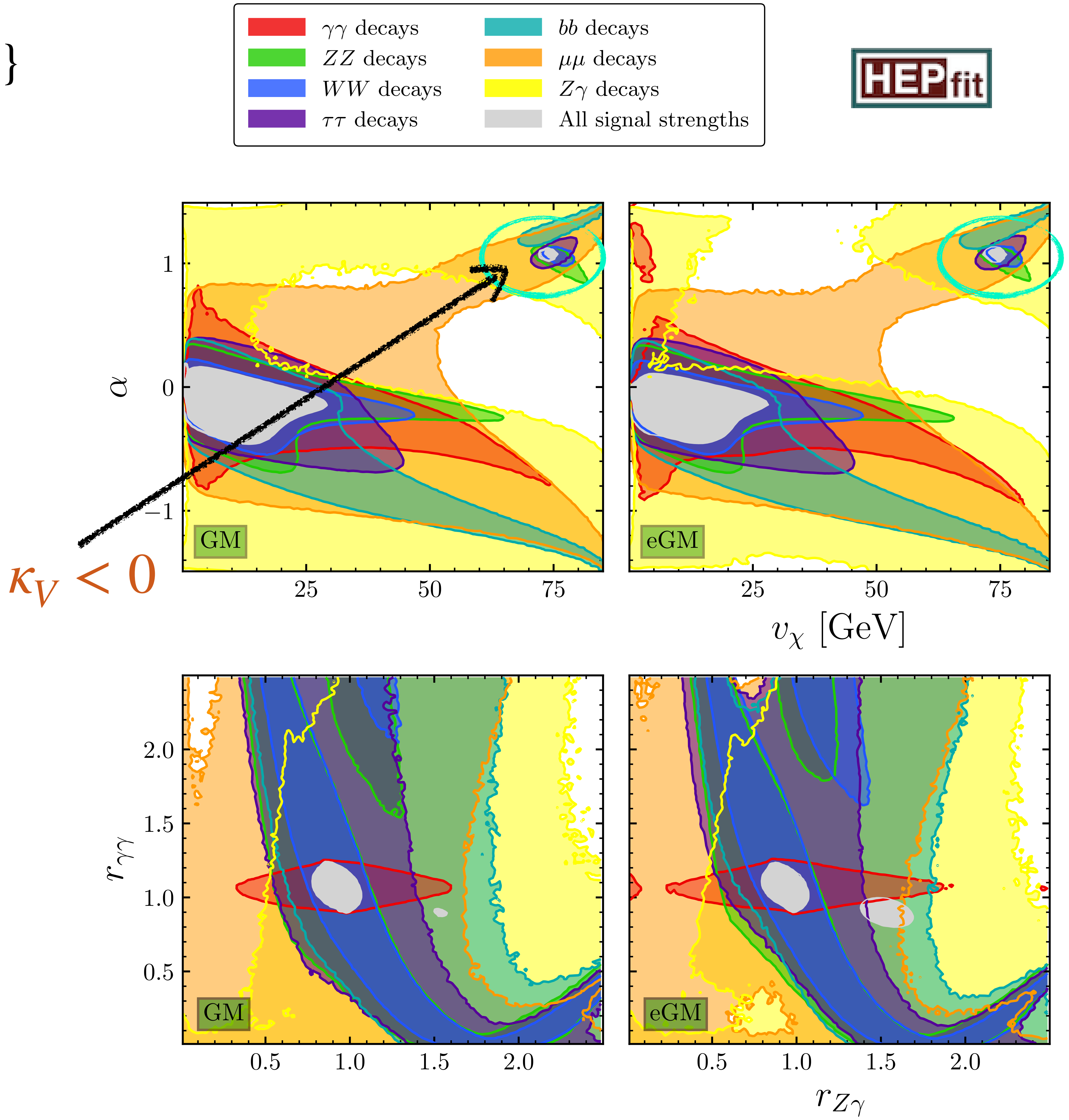
$$i \in \{ggF, bbh, VBF, Wh, Zh, tth, th\}$$

$$f \in \{ZZ, WW, \gamma\gamma, Z\gamma, \mu\mu, bb, \tau\tau\}$$





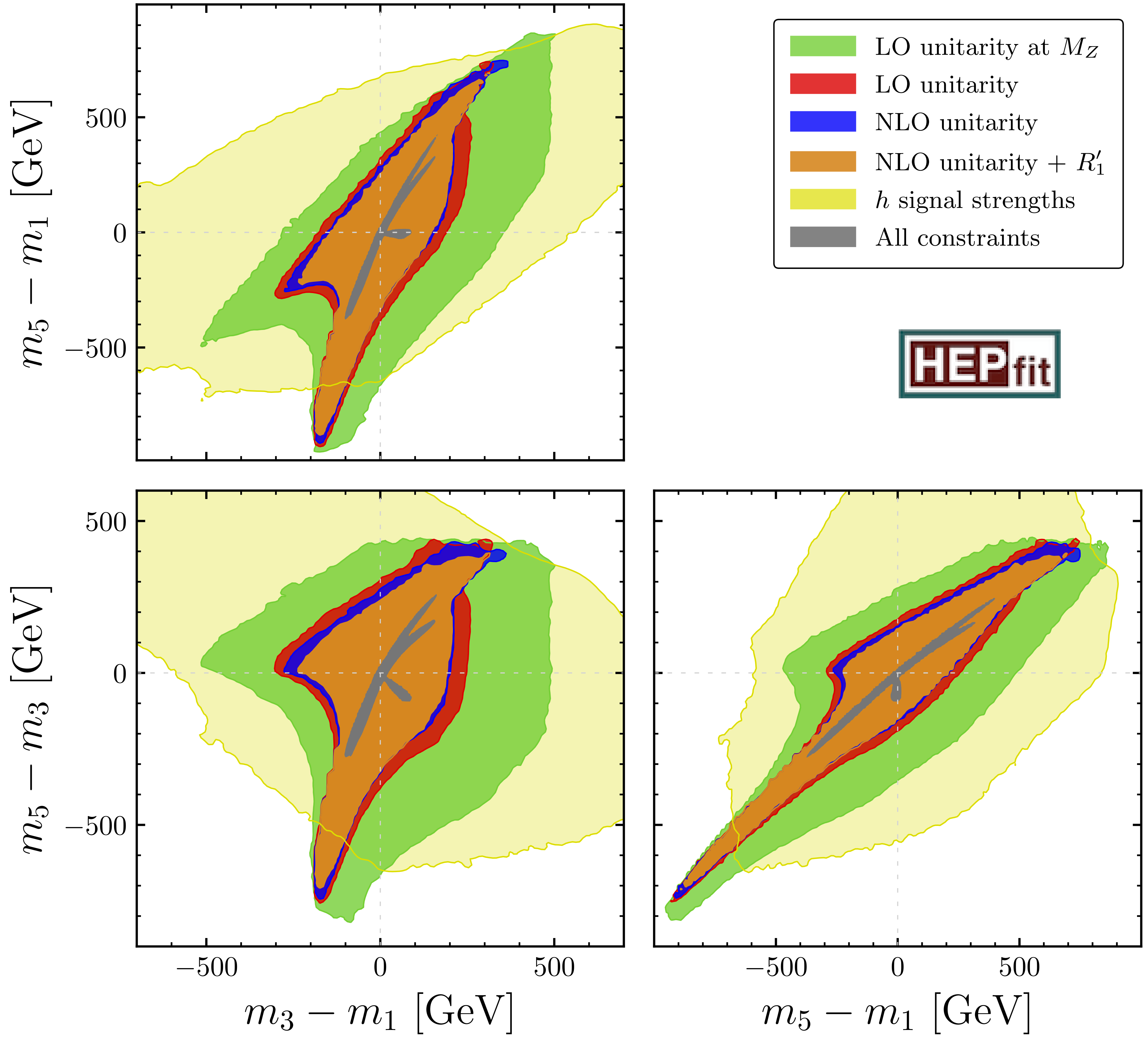
arXiv: 2206.09466

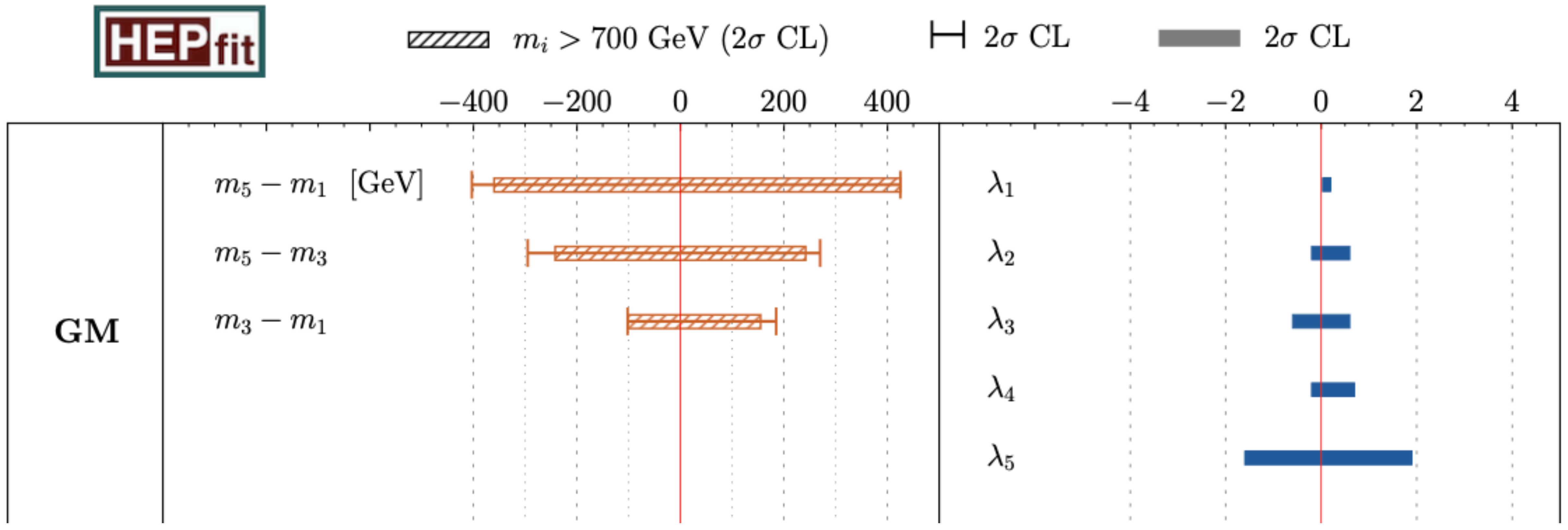


Latest Run 2 LHC data put a stringent bound on triplet VEV , $v_\chi < 32$ GeV

Strongly disfavour $|\kappa_V| > 1.05$ @ 95.4% CL

Status of GM Model (combined fit)





More restrictive parameter space from improved theoretical constraints

Maximum mass splitting reduced ~ 100 GeV from the literature

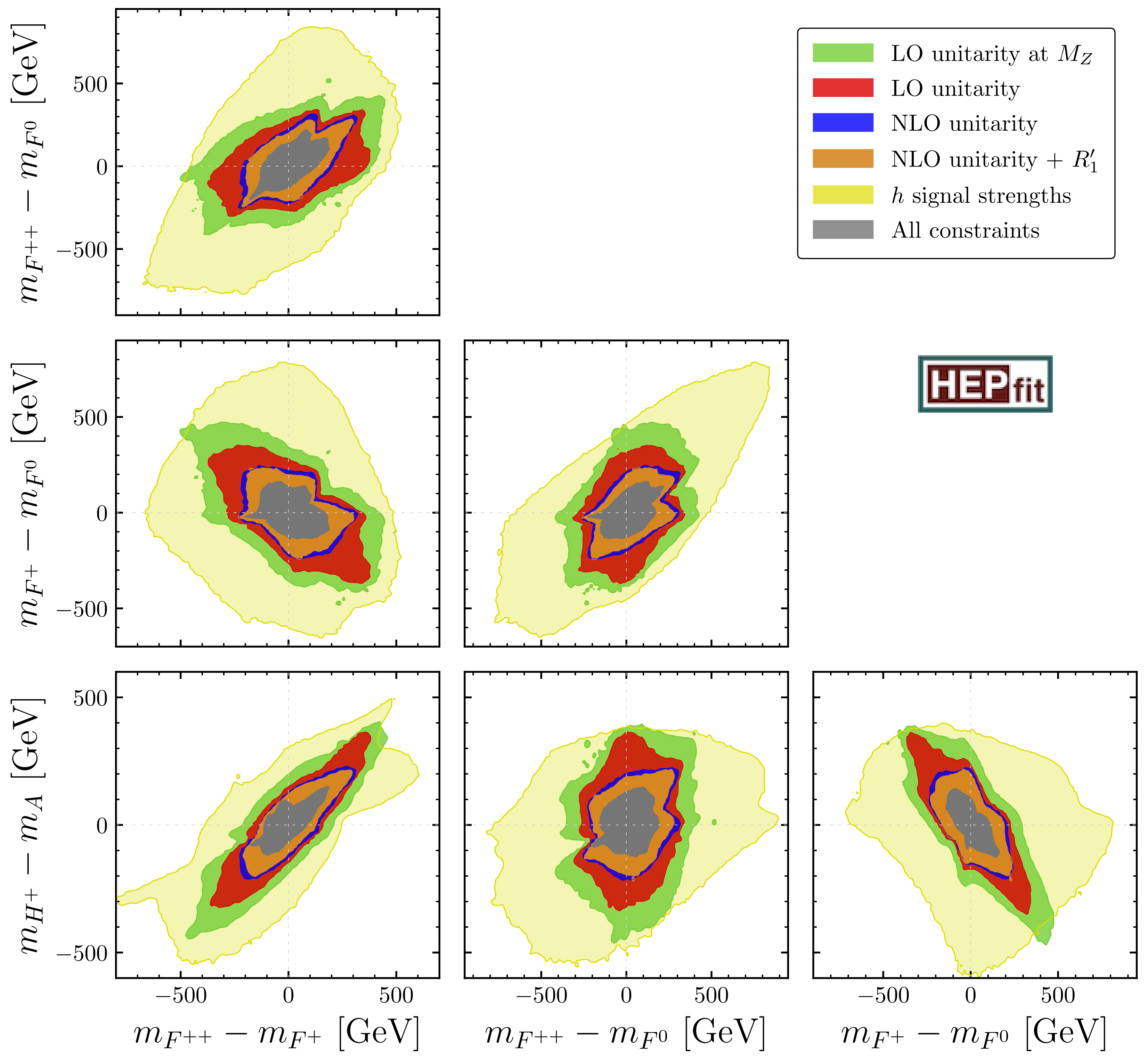
Quartic couplings can't exceed 1.9 @ one-loop

... while about 3.0 @ tree-level

[arXiv: 1807.10660]

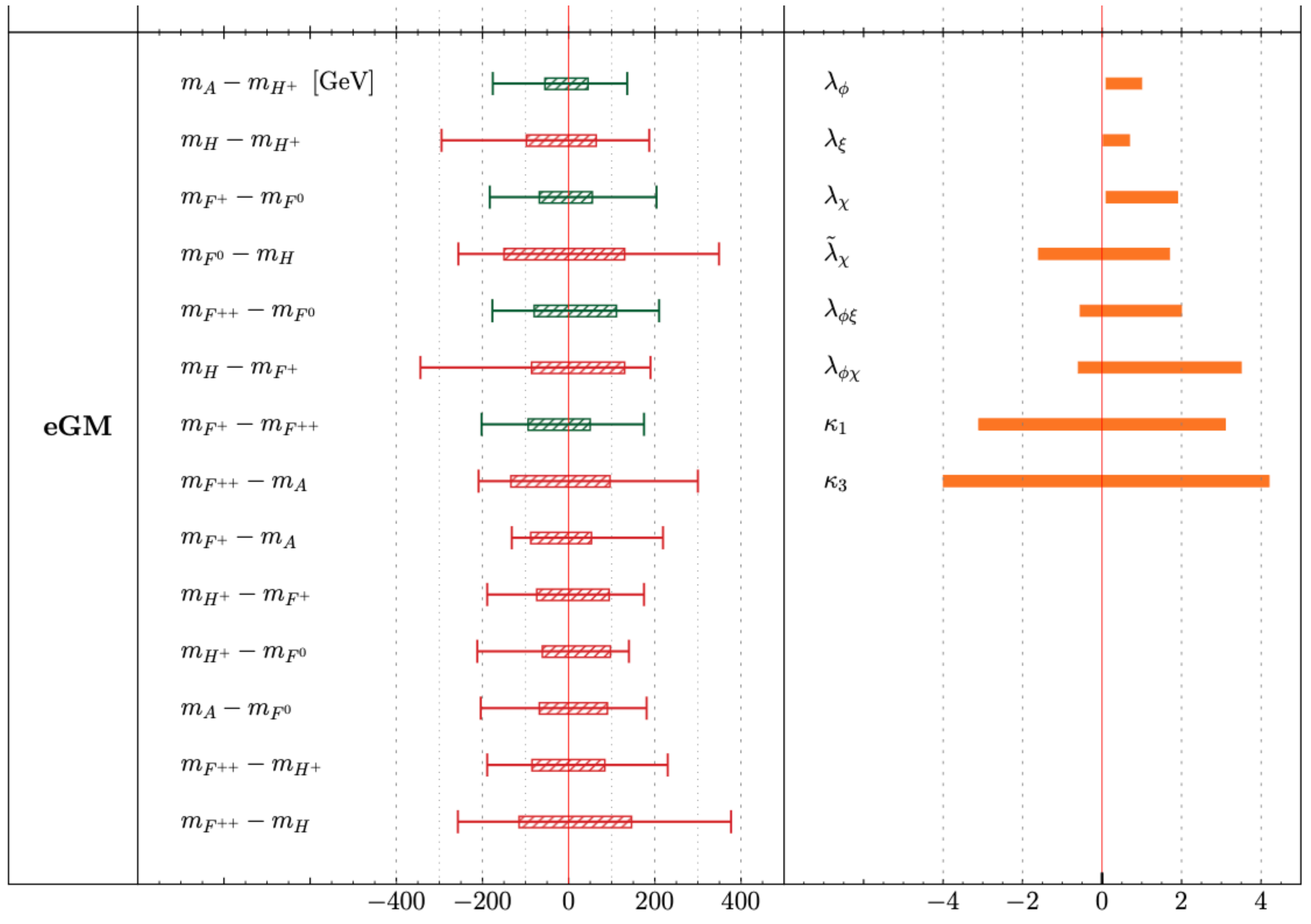
D. Chowdhury, P. Mondal, S.S. 2404.18996

Status of eGM Model (combined fit)



D. Chowdhury, P. Mondal, S.S. 2404.18996

@ 95.4% CL limit on mass differences and quartic couplings

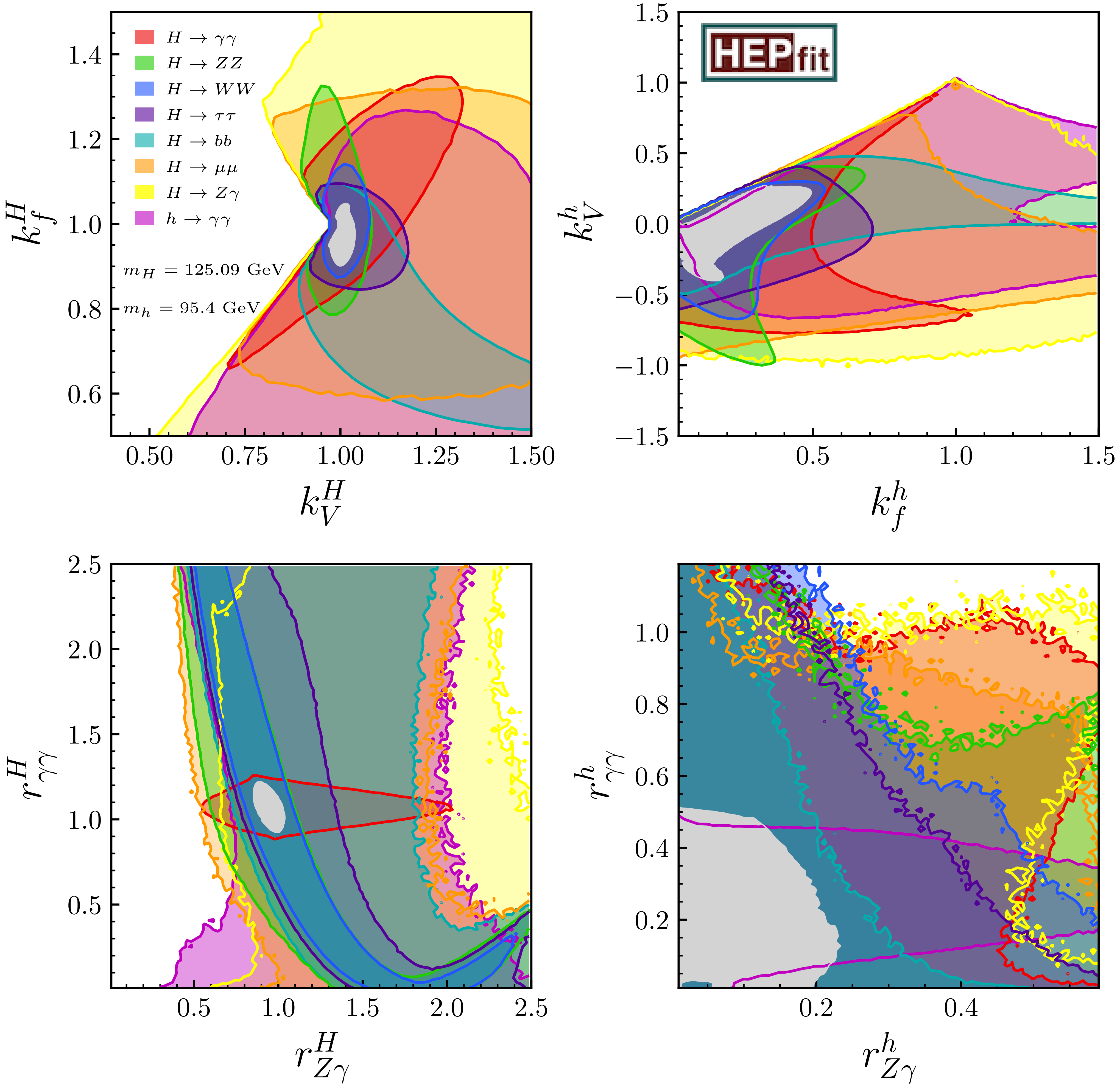


Maximum mass splitting within custodial multiplets

~ 210 **GeV** @ 95.4% CL

➡ Flavor or electroweak precision data could be used to constrain the model further. *(Work in progress ...)*

95 GeV Higgs Results



$$\kappa_f^h \kappa_V^h + \kappa_f^H \kappa_V^H = 1$$

$|\kappa_V^h| > 0.4$

$|\kappa_V^H| > 1.05$

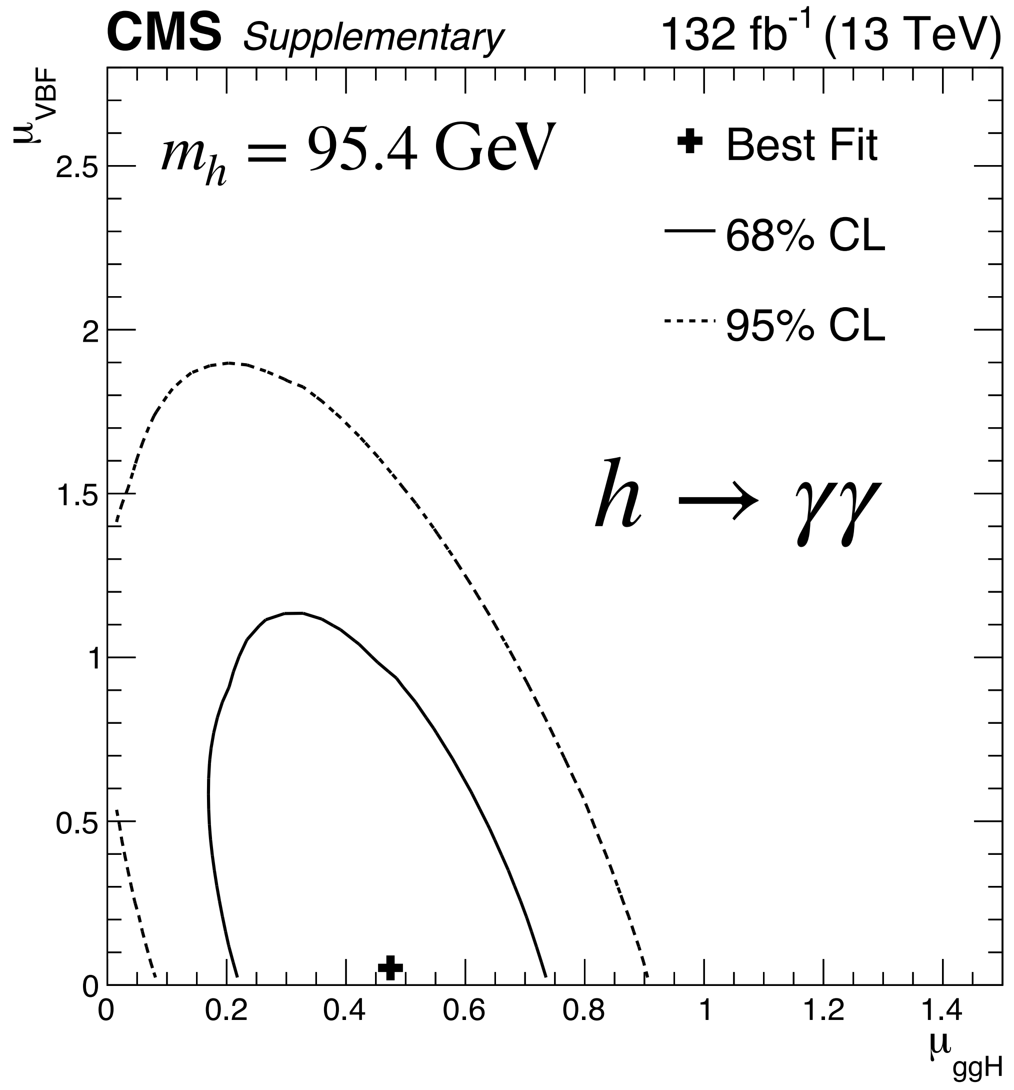
} excluded @ 95.4% CL

$$m_h = 95.4 \text{ GeV}$$

$$m_H = 125.09 \text{ GeV}$$

$$\mu_{\gamma\gamma}^{\text{ATLAS}} = \frac{\sigma^{\text{exp}}(pp \to \phi \to \gamma\gamma)}{\sigma^{\text{SM}}(pp \to h \to \gamma\gamma)} = 0.18^{+0.10}_{-0.10}$$

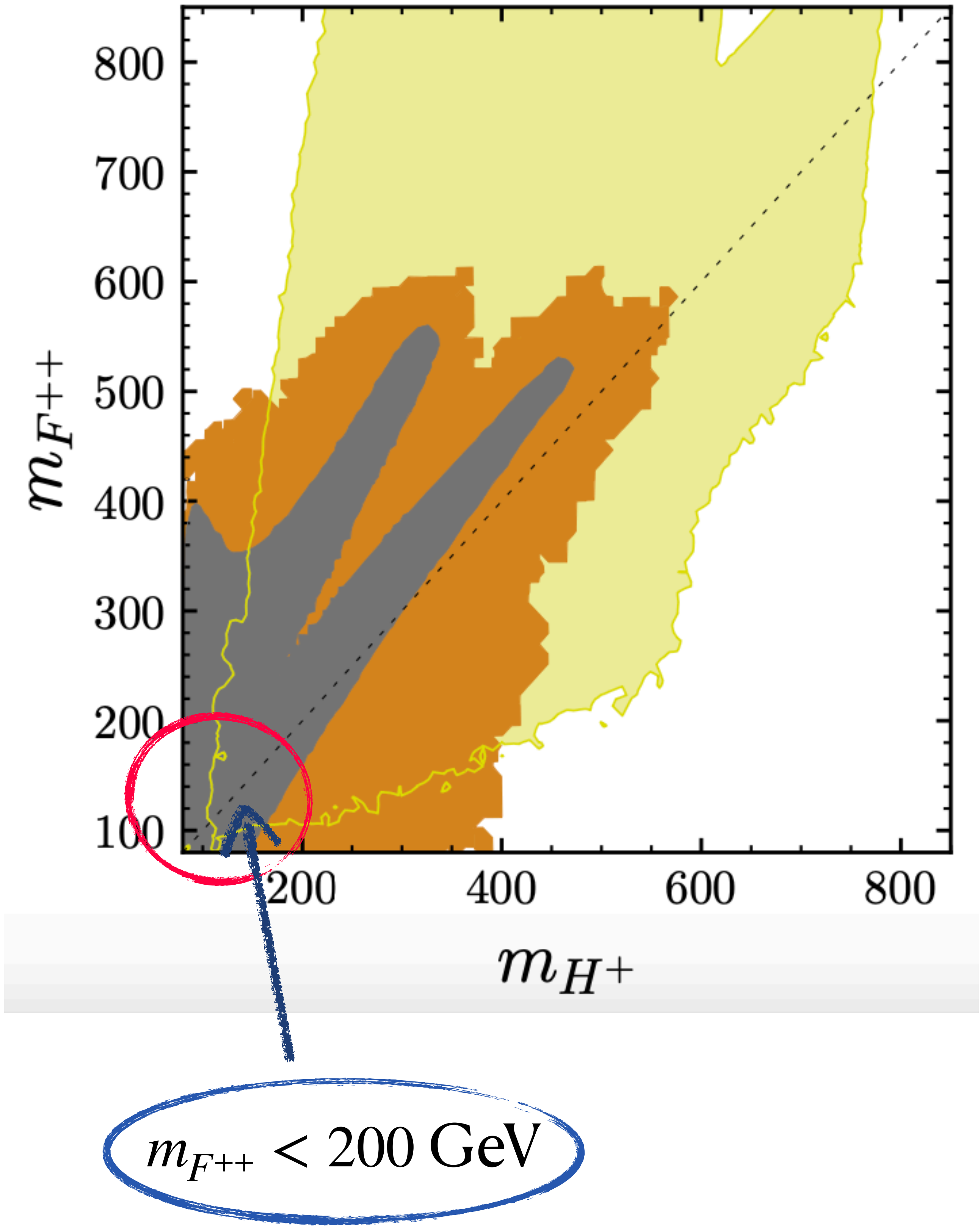
arXiv: 2306.03889

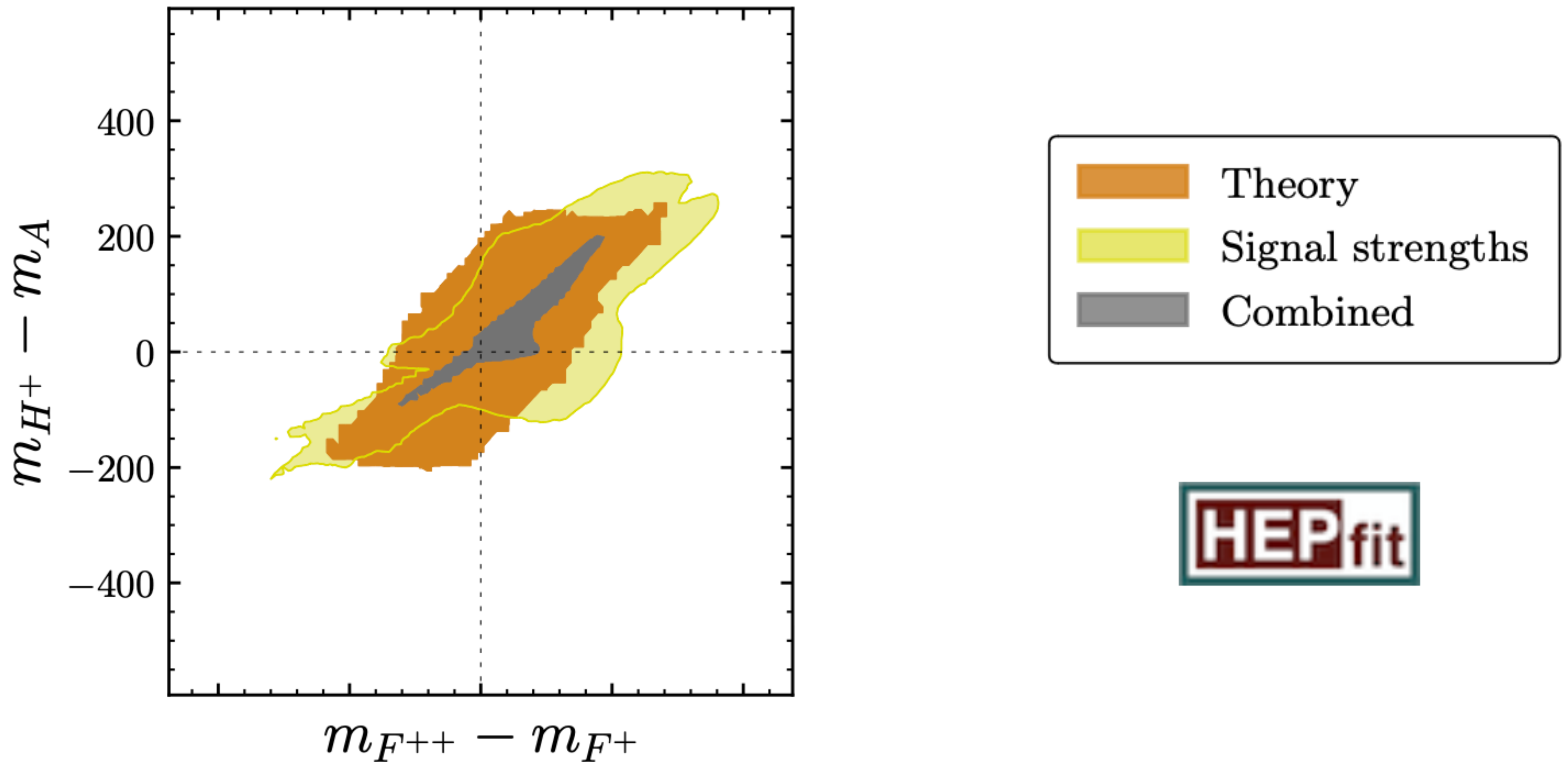


CMS-HIG-20-002

Constraints on additional Higgs bosons

Upper bound on the masses of additional heavy Higgs bosons is ~ 550 GeV @ 95.4% CL





allowed by NLO unitarity and Higgs data @ 95.4% CL

……yet to be explored at the LHC or in future colliders

Summary

* Triplet scalar extension of SM with custodial symmetry at tree-level without requiring global $SU(2)_L \times SU(2)_R$ symmetry in the potential gives extended Georgi-Machacek (eGM) model

* Improved theoretical constraints (NLO unitarity with positivity) significantly refine the parameter space of the GM and eGM models

* Triplet VEV gets more and more constrained from the LHC data

* Regions where $|\kappa_V| > 1.05$ are disfavoured by the latest LHC data

* Mass splittings within custodial multiplets introduce new decay modes in eGM model

* In the presence of a 95 GeV Higgs, the upper bound on the masses of additional heavy Higgs bosons is $\sim$ 550 GeV

Thank You

Backup slides

Collider Phenomenology

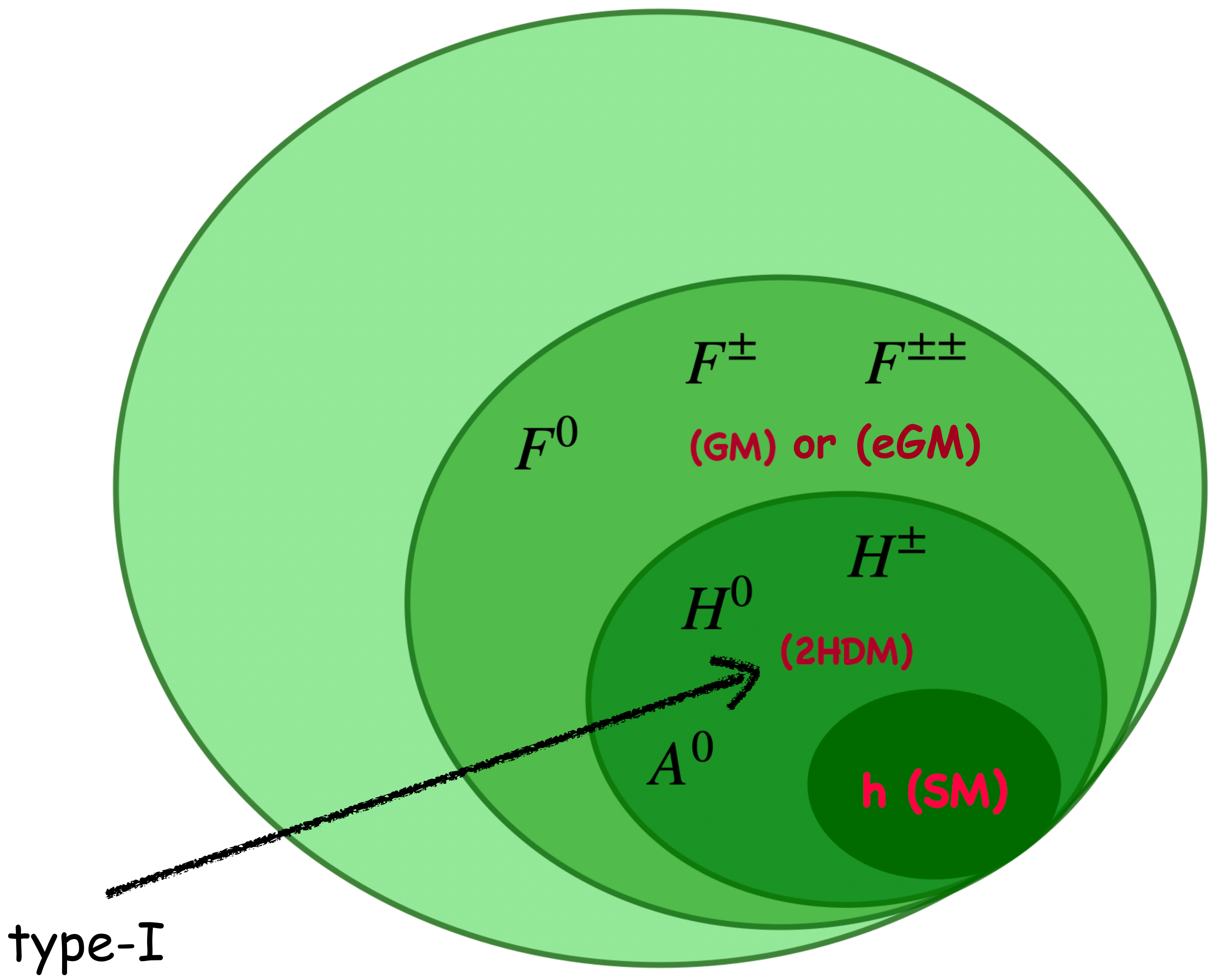
- Yukawa sector :

Only the doublet couples to fermions

triplet VEV (v_χ) : $v_\phi^2 + 8 v_\chi^2 = v^2$ and $\tan\beta = \dfrac{v_\phi}{2\sqrt{2} v_\chi}$

v_χ ↓ $\tan\beta$ ↑

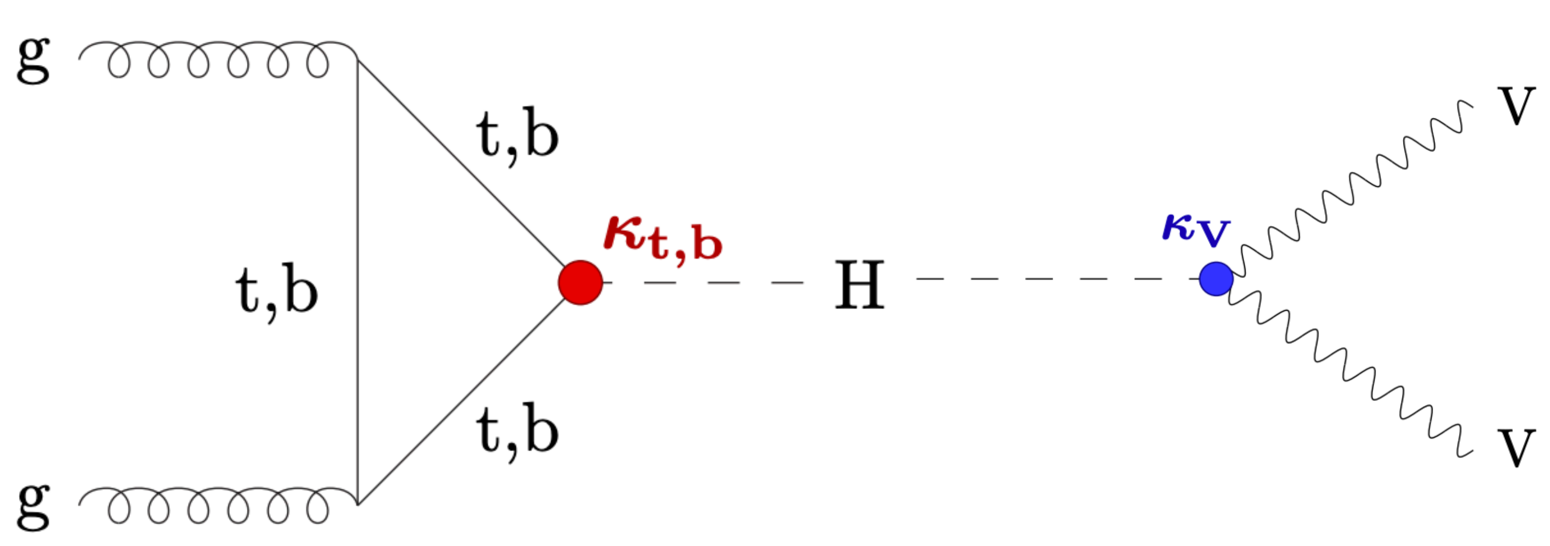
……Similar phenomenology as in type-I 2HDM



Additional features :

The addition of a singly charged scalar (F^+) coupled to fermions,
along with the presence of a doubly charged scalar,
makes these models highly interesting for collider studies.

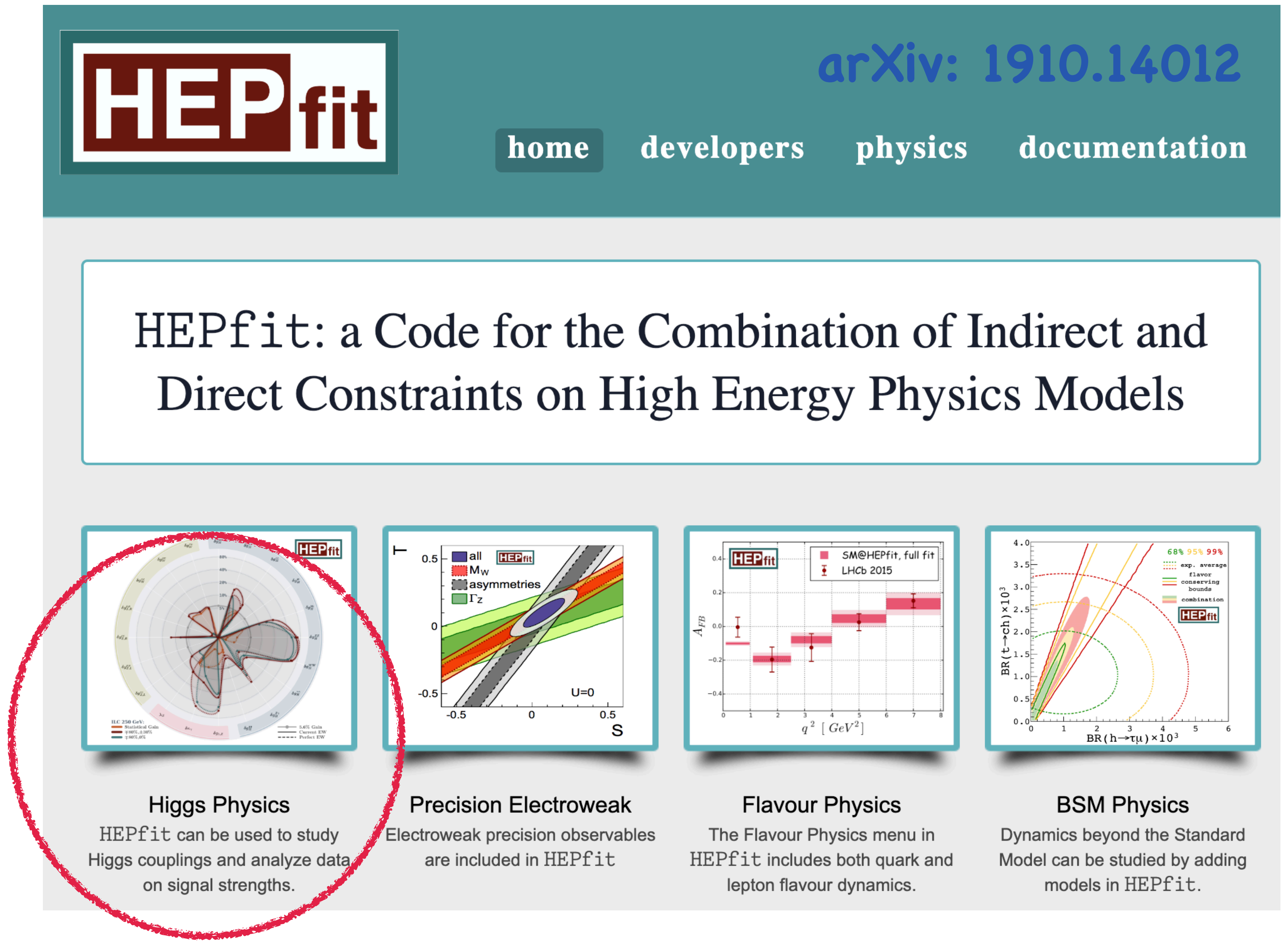
Higgs Signal Strengths : HEPfit Implementation



$$i \in \{ggF, bbh, VBF, Wh, Zh, tth, th\}$$

$$f \in \{ZZ, WW, \gamma\gamma, Z\gamma, \mu\mu, bb, \tau\tau\}$$

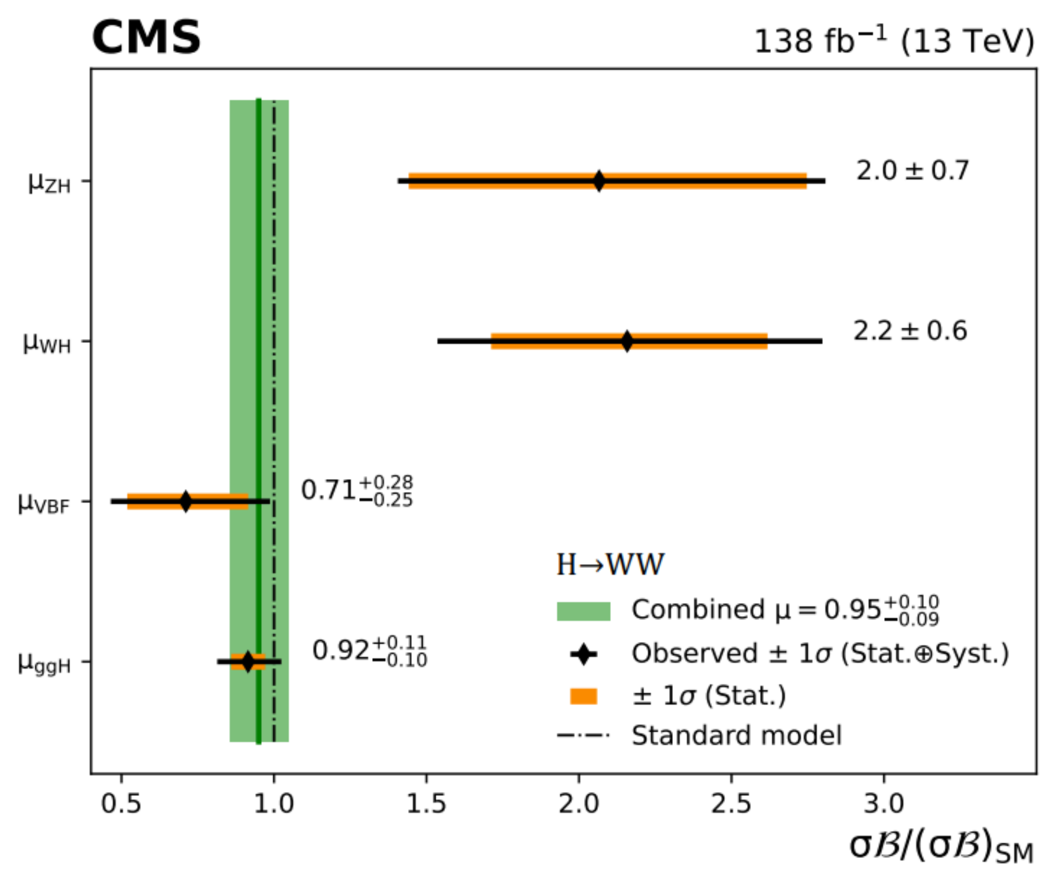
$$\mu_i^f = \frac{\sigma B\,(i \to H \to f)}{\sigma B_{SM}\,(i \to H \to f)}$$

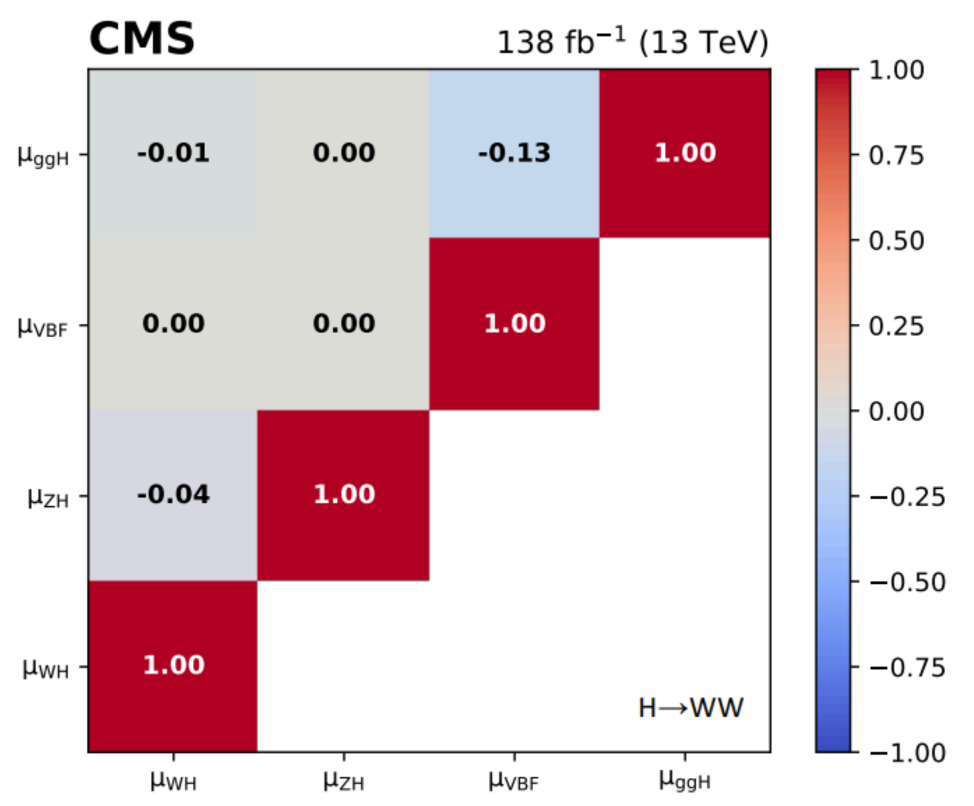


http://hepfit.roma1.infn.it

- Make all possible observables μ_i^f for different production and decay modes
- Fit to the ALTAS and CMS data on (correlated) observables μ_i^f for a BSM model
- Present the results on the (new) observables from the combined fit

$$\kappa_V = c_\alpha c_\beta - \sqrt{\frac{8}{3}} s_\alpha s_\beta\,, \quad \text{and} \quad \kappa_f = \frac{c_\alpha}{c_\beta}\,,$$





arXiv: 2206.09466

Higgs Signal Strengths : LHC data

ATLAS Run 2

Signal strength	Value	Correlation matrix						$\mathcal{L}$ [fb^{-1}]	Source
$\mu^{\gamma\gamma}_{\mathrm{ggF,bbh}}$	1.04 ± 0.10	1	−0.13	0	0	0	0	139	[18]
$\mu^{\gamma\gamma}_{\mathrm{VBF}}$	1.20 ± 0.26	−0.13	1	0	0	0	0		
$\mu^{\gamma\gamma}_{\mathrm{Wh}}$	1.5 ± 0.55	0	0	1	−0.37	0	−0.11		
$\mu^{\gamma\gamma}_{\mathrm{Zh}}$	-0.2 ± 0.55	0	0	−0.37	1	0	0		
$\mu^{\gamma\gamma}_{\mathrm{tth}}$	0.89 ± 0.31	0	0	0	0	1	−0.44		
$\mu^{\gamma\gamma}_{\mathrm{th}}$	3 ± 3.5	0	0	−0.11	0	−0.44	1		
μ^{ZZ}_{ggF}	0.95 ± 0.1	1	−0.22	−0.27	0			139	[4]
μ^{ZZ}_{VBF}	1.19 ± 0.45	−0.22	1	0	0				
μ^{ZZ}_{Vh}	1.43 ± 1.0	−0.27	0	1	−0.18				
μ^{ZZ}_{tth}	1.69 ± 1.45	0	0	−0.18	1				
$\mu^{ZZ}_{\mathrm{incl.}}$	1.0 ± 0.1							139	[4]
$\mu^{WW}_{\mathrm{ggF,bbh}}$	1.15 ± 0.135							139	[17]
μ^{WW}_{VBF}	0.93 ± 0.21								
$\mu^{WW}_{\mathrm{ggF,bbh,VBF}}$	1.09 ± 0.11								
$\mu^{\tau\tau}_{\mathrm{VBF}}$	0.90 ± 0.18	1	−0.24	0	0			139	[13]
$\mu^{\tau\tau}_{\mathrm{ggF,bbh}}$	0.96 ± 0.31	−0.24	1	−0.29	0				
$\mu^{\tau\tau}_{\mathrm{Vh}}$	0.98 ± 0.60	0	−0.29	1	0				
$\mu^{\tau\tau}_{\mathrm{tth,th}}$	1.06 ± 1.18	0	0	0	1				
μ^{bb}_{VBF}	0.95 ± 0.37							126	[9]
μ^{bb}_{Wh}	0.95 ± 0.26							139	[6]
μ^{bb}_{Zh}	1.08 ± 0.24							139	[6]
μ^{bb}_{Vh}	1.02 ± 0.17							139	[6]
$\mu^{bb}_{\mathrm{tth,th}}$	0.35 ± 0.35							139	[12]
$\mu^{\mu\mu}_{\mathrm{pp}}$	1.2 ± 0.6							139	[7]
$\mu^{Z\gamma}_{\mathrm{pp}}$	2.0 ± 0.95							139	[5]

CMS Run 2

Signal strength	Value	Correlation matrix				$\mathcal{L}$ [fb^{-1}]	Source
$\mu^{\gamma\gamma}_{\mathrm{ggh,bbh}}$	1.07 ± 0.11					137	[11]
$\mu^{\gamma\gamma}_{\mathrm{VBF}}$	1.04 ± 0.32						
$\mu^{\gamma\gamma}_{\mathrm{Vh}}$	1.34 ± 0.34						
$\mu^{\gamma\gamma}_{\mathrm{tth,th}}$	1.35 ± 0.31						
$\mu^{ZZ}_{\mathrm{ggh,bbh,tth,th}}$	0.95 ± 0.13	1	−0.11			137	[10]
$\mu^{ZZ}_{\mathrm{VBF,Vh}}$	0.82 ± 0.34	−0.11	1				
μ^{WW}_{ggh}	0.92 ± 0.11	1	−0.13	0	0	138	[16]
μ^{WW}_{VBF}	0.71 ± 0.26	−0.13	1	0	0		
μ^{WW}_{Zh}	2.0 ± 0.7	0	0	1	0		
μ^{WW}_{Wh}	2.2 ± 0.6	0	0	0	1		
$\mu^{\tau\tau}_{\mathrm{incl.}}$	0.93 ± 0.12					138	[15]
$\mu^{\tau\tau}_{\mathrm{ggh}}$	0.97 ± 0.19						
$\mu^{\tau\tau}_{\mathrm{qqh}}$	0.68 ± 0.23						
$\mu^{\tau\tau}_{\mathrm{Vh}}$	1.80 ± 0.44						
μ^{bb}_{qqh}	1.59 ± 0.60	1	−0.75			90.8	[19]
μ^{bb}_{ggh}	-2.7 ± 3.89	−0.75	1				
$\mu^{\mu\mu}_{\mathrm{ggh,tth}}$	0.66 ± 0.67	1	−0.24			137	[8]
$\mu^{\mu\mu}_{\mathrm{VBF,Vh}}$	1.85 ± 0.86	−0.24	1				
$\mu^{Z\gamma}_{\mathrm{pp}}$	2.4 ± 0.9					138	[14]